ELSEVIER

CrossMark

Procedia Engineering

Volume 143, 2016, Pages 427–434

Advances in Transportation Geotechnics 3 . The 3rd International Conference on Transportation Geotechnics (ICTG 2016)

Procedia Engineering

Modelling of Plastic Culvert and Road Embankment Interaction in 3D

Pauli Kolisoja[1*] and Antti Kalliainen[1†]

[1] *Tampere University of Technology, Tampere, Finland*

pauli.kolisoja@tut.fi, antti.kalliainen@tut.fi

Abstract

A series of 3D Finite Element simulations was performed to investigate the effect of different factors influencing the distortions undergone by a plastic culvert tube while subject to external loading from a heavy truck. The applied simulation model was verified by full-scale loading tests carried out on a number of actual culvert installation sites. Based on the results of the study, it can be concluded that both installation depth and quality of the material surrounding the culvert have a dominant effect on culvert distortions while the effects of material quality above the culvert and the type of tyre configuration transmitting the wheel load are much less pronounced.

Keywords: plastic culvert, distortion, Finite Element, simulation, installation depth, subgrade quality

1 Introduction

Operative culverts play an important role in an operative drainage system vital for guaranteeing the appropriate long-term performance of a road or railway structure. Depending on the type and quality level of the road or railway, however, the requirements set for culverts vary. This applies both to the culvert materials and minimum installation depths as well as the transition structures that need to be built around the culvert.

On roads with low traffic volumes and correspondingly thin structural layers, the installation depths of culverts are typically rather shallow. It means that the traffic loads from heavy vehicles induce marked stresses and strains on the culvert pipe, whereas at greater installation depths the stresses from overburden pressure are much more pronounced.

With regard to culvert materials, plastic has been gaining increasing popularity especially in low volume road applications. The main reasons are its competitive price and the fact that plastic culverts do not suffer from the same type of corrosion problems as steel culverts. Since they can also be

[*] Corresponding author

[†] Co-author, who performed the FE modelling presented in the paper

Selection and peer-review under responsibility of the Scientific Programme Committee of ICTG 2016

doi:10.1016/j.proeng.2016.06.054

installed as continuous elements that are several meters long, the opening and cracking of joints in between culvert elements is not as much a problem as it can be with concrete culverts.

Interaction between the culvert structure and the surrounding soil material depends also very much on the culvert material – primarily on the difference in stiffness between the culvert and surrounding soil. While a concrete culvert transmits the external load applied on it mainly by its own rigidity, the mechanical resistance of a plastic culvert to external loading is mainly based on the lateral support the culvert obtains from the surrounding soil, as the plastic tube compresses vertically and expands horizontally.

The analytical design models normally applied in assessing the distresses of a plastic culvert subjected to external loading are fairly robust, especially as concerns the properties of the surrounding soil material (Spangler, 1941; Molin, 1981; CEN/TR 1295-3, 2007). Neither do they take into account the whole structural system of the road including both the properties of the structural layers above the culvert and the underlying subgrade. During the last few years more advanced studies combining the results of experimental testing to the possibilities opened by modern numerical analysis tools have been conducted by several researchers (Kraus;Oh;& Fernando, 2014; Arockiasamy;Chaallal;& Limpeteeprakarn, 2006; Kang;Jung;& Ahn, Cover requirements of thermoplastic pipes used under highways, 2013; Kang;Han;Kang;& Yoo, 2009). In quite a few of the recent studies special attention has also been put on the behaviour of culvert joints (Sheldon;Sezen;& D., 2015; Moore & Sezen, 2012) which are likely to be the weakest point of a culvert structure.

This paper describes a study which included a sensitivity analysis of the mechanical behaviour of an 800 mm diameter corrugated HDPE plastic culvert pipe installed as a single continuous element in the conditions of a typical low volume road structure in Finland. The variables of the analysis performed with Finite Element program PLAXIS-3D (Brinkreve;Engin;& Swolfs, 2012) were installation depth of the culvert, quality of road pavement materials, quality of subgrade soil and type of tyre configuration transmitting the wheel load onto the road surface. Validation of the FE modelling carried out in the project was based on full-scale loading tests performed at instrumented plastic culvert sites located on low volume roads with gravel surface.

2 3D FE Model of the Plastic Culvert Installation Sites

A schematic picture of the Finite Element Model used in this study is shown in Figure 1. Dimensions of the model were 12 m in the culvert direction, 8 m in the road direction and 5 m in the vertical direction. The element type used for modelling the structural layers of the road as well as subgrade soil was made using ten-node tetrahedral elements while a cylindrical plate element with a bending stiffness equal to that of the actual profiled plastic tube was used for modelling the culvert.

The model geometry did not consider side ditches of the road or side slopes of the road surface, but the model had a flat top surface from side to side. Since actual culverts installed on low volume roads typically do not have any transition structures around them, but the surrounding backfill is made with the subgrade material excavated from the site, the model was built correspondingly (Figure 1). The wheel loads acting on the top of the road were applied in the model via horizontally positioned octagonal plate elements of the same size as the actual contact areas between the vehicle's tyres and road surface.

The material models used were the following: Hardening Soil (HS) for the structural layers of the road, Mohr-Coulomb (MC) model in undrained conditions for the subgrade soil, and Linear Elastic (LE) model for the culvert pipe. The respective material parameters summarised later in Section 4 were selected based on earlier experience from similar type of road structures and aggregate materials (e.g. Kolisoja 2014 and Kolisoja et al. 2015). In assessing stiffness parameters and actual thicknesses of the structural layers the results of Dynamic Cone Penetrometer (DCP) tests performed on the culvert installation sites were utilized.

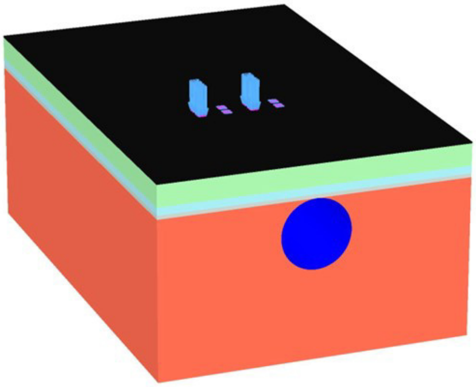

Figure 1: Schematic picture of the used FE model.

3 Verification of the FE Model

In connection with the current project, full-scale loading tests were performed at four plastic culvert installation sites where the culverts were instrumented for measuring changes in both the vertical and horizontal diameter of the culvert at three different cross-sections along the tube (Figure 2). At two of the measurement sites the culvert diameter was 600 mm, and at the other two 800 mm.

Figure 2: Installation of the displacement transducers used to monitor changes in the vertical and horizontal diameters of a plastic culvert.

The vehicle used in the full-scale loading tests was a combination of a truck and trailer with the following axle loads: 75 kN on the truck steering axle, 210 kN on the truck double bogie, 100 kN on the trailer front axle, and 180 kN on the trailer double bogie. The distance between the axles of the truck double bogie was 1.3 m and that of the trailer double bogie 2.0 m. Inflation pressure of all tyres was from 770 to 900 kPa. With the exception of the truck steering axle, all axles had dual tyres 275 mm to 315 mm wide. In the following, only the results received with the 210 kN truck double boogie are presented.

Responses of the diameter change measuring devices were recorded continuously while the loading vehicle passed over the culvert sites several times using slightly different wheel paths in the cross-sectional direction of the road. In Figures 3 to 5, the measured maximum values of culvert compression in the vertical direction and expansion in the horizontal direction under the axles of the 210 kN truck double bogie are shown for a 600 mm diameter plastic culvert pipe installed at the depth of 650 mm, and 800 mm diameter plastic culvert pipes installed at depths of 800 mm and 200 mm, respectively. All figures indicate clearly that the maximum diameter change values were recorded when the centre line of a pair of dual wheels was nearest the measurement cross-section of the culvert pipe. As the distance between the wheel path and the measurement cross-section increases towards the right side of each diagram, the measured changes in the culvert diameter approach zero. The respective results of FE modelling corresponding to the loading effect of the truck double bogie are also shown in Figures 3 to 5.

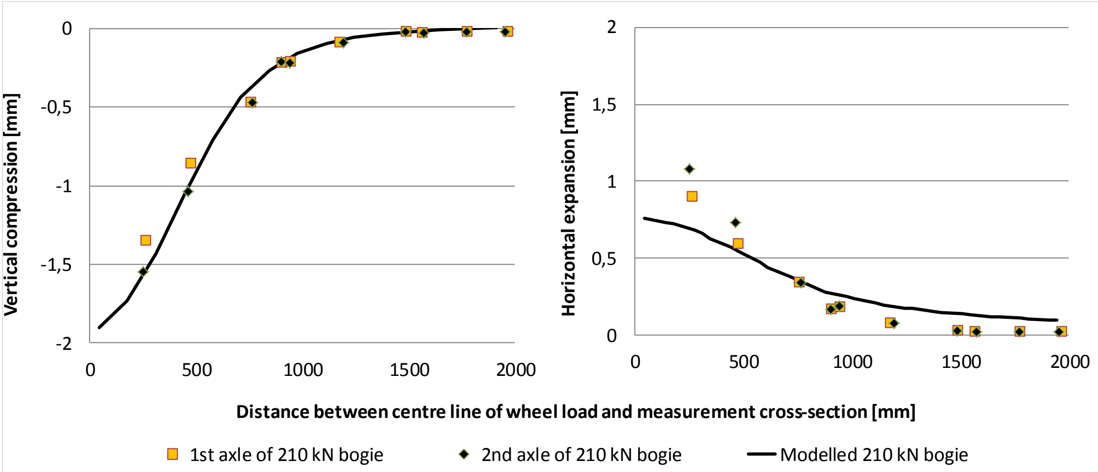

Figure 3: Measured and modelled changes in the vertical and horizontal diameter of a 600 mm plastic culvert pipe installed at the depth of 650 mm.

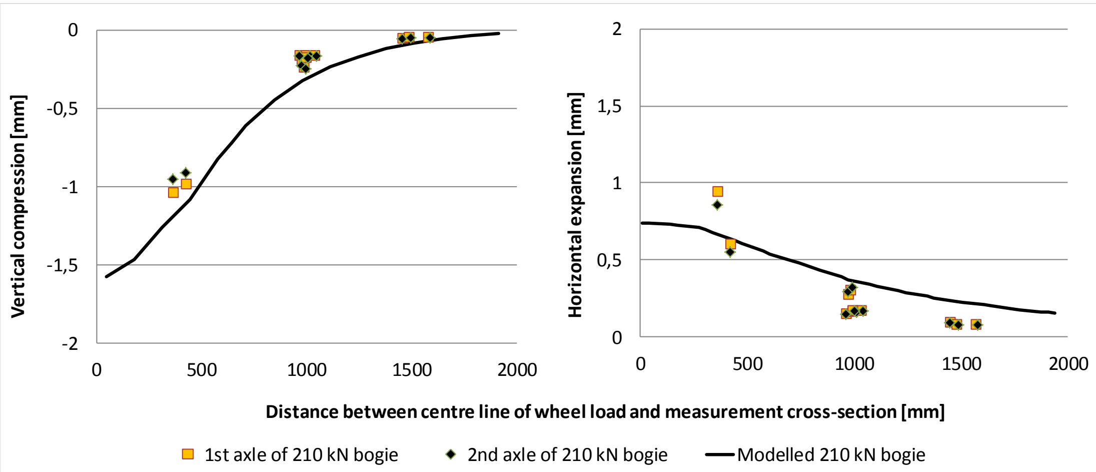

Figure 4: Measured and modelled changes in the vertical and horizontal diameter of an 800 mm plastic culvert pipe installed at the depth of 800 mm.

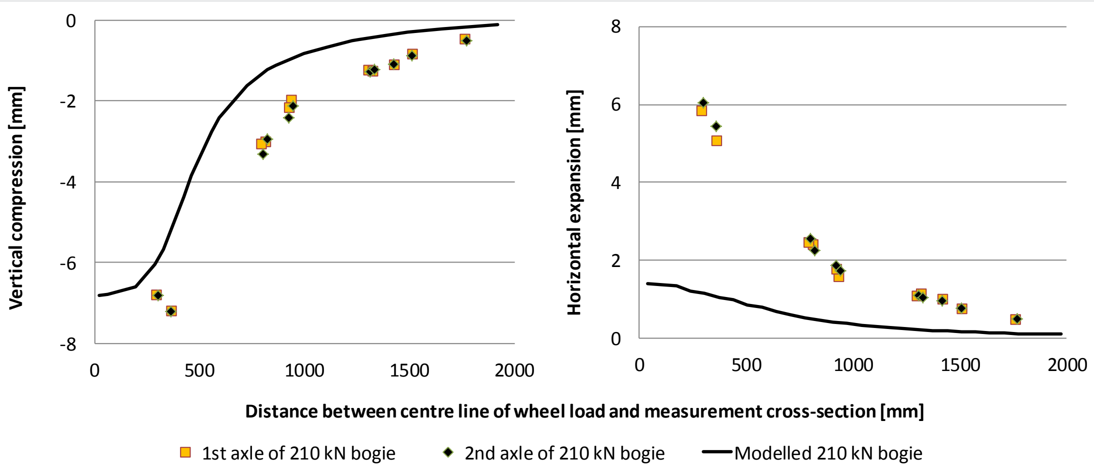

Figure 5: Measured and modelled changes in the vertical and horizontal diameter of an 800 mm plastic culvert pipe installed at the depth of 200 mm.

The results presented in Figures 3 to 5 indicate clearly that, especially as concerns vertical compression of the culvert pipes, the results of FE modelling match very well the responses measured on site. Regarding the horizontal expansion of the culverts, the results are not quite as consistent, but the compatibility of measured and FE simulated responses is still reasonably good. The only exception is the horizontal expansion of the 800 mm culvert installed at the depth of only 200 mm. In that case, the values predicted by the FE analysis at the mid-level of the culvert pipe are only a fraction of those measured on site. That is probably due to the exceptionally shallow installation conditions resulting in more localised nature of culvert distortions the FE simulation was not able to reproduce. At this point it is also important to note that during the on site measurements the actual wheel loads were moving from one side of the culvert pipe to the other while in the FE simulation the wheel loads were all the time acting symmetrically along the central line of the culvert.

4 Sensitivity Analyses

The FE model simulations validated as described above were used to perform a series of sensitivity analyses on the various factors influencing the distortions which plastic culverts undergo in different installation conditions. The first set of sensitivity analyses considered installation depth of the culvert, the second quality of road pavement materials and subgrade soil, and the third the type of tyre configuration transmitting the wheel load to the road surface. The respective FE model material parameters used in the simulations have been summarised in Table 1. The set of material parameters referred to as the reference case (N = 1) and shown on a shaded background below is basically the same as that used in the FE simulations of the actual 800 mm diameter plastic culverts loaded on site (Figures 4 and 5). Regarding the other simulations, only the material parameters different from the reference case are shown.

The results of the first set of sensitivity analyses are summarised in Figure 6 which presents the simulated changes in vertical and horizontal diameter of the culverts installed at different depths as a function of distance from the centre line of the wheel load. The figure indicates clearly that as soon as installation depth gets smaller than culvert diameter, distortions of the culvert pipe increase rapidly. At least qualitatively the result compares very well with the soil pressures measured by others around flexible pipes with different diameter and burial depth (Chaallal;Arockiasamy;& Godat, 2015).

			Structural layer 0 … 150 mm / 150 … 400 mm							Subgrade soil			
N	Z mm	T	c' kPa	φ °	ψ °	E_{50}^{ref} MPa	E_{oed}^{ref} MPa	E_{ur}^{ref} MPa	K_0^{nc} -	E' MPa	ν -	s_u kPa	s_u^{incr} kPa/m
1	800	D	20/10	50/45	20/15	225/175	225/175	450/350	0.31/0.33	40	0.4	35	1,5
2	1000	D											
3	600	D											
4	400	D											
5	200	D											
6	800	D	10/8	45/40	15/10				0.33/0.37				
7	800	D								20		20	
8	800	D	10/8	45/40	15/10				0.33/0.37	20		20	
9	400	S											

Notations: N = FE simulation number, Z = Installation depth of culvert, T = Tyre type (D = Dual, S = Single), c' = Apparent cohesion, φ = Friction angle, ψ = Dilation angle, E_{50}^{ref} = Secant stiffness in standard drained triaxial test, E_{oed}^{ref} = Tangent stiffness for primary oedometer loading, E_{ur}^{ref} = Unloading-reloading stiffness, K_0^{nc} = K_0-value for normal consolidation, E' = Stiffness modulus, ν = Poisson's ratio, s_u = Undrained shear strength, s_u^{inc} = s_u increment per metre of depth.

Table 1: Variables of the performed FE simulations. Combined thickness of the structural layers was 400 mm in all simulations.

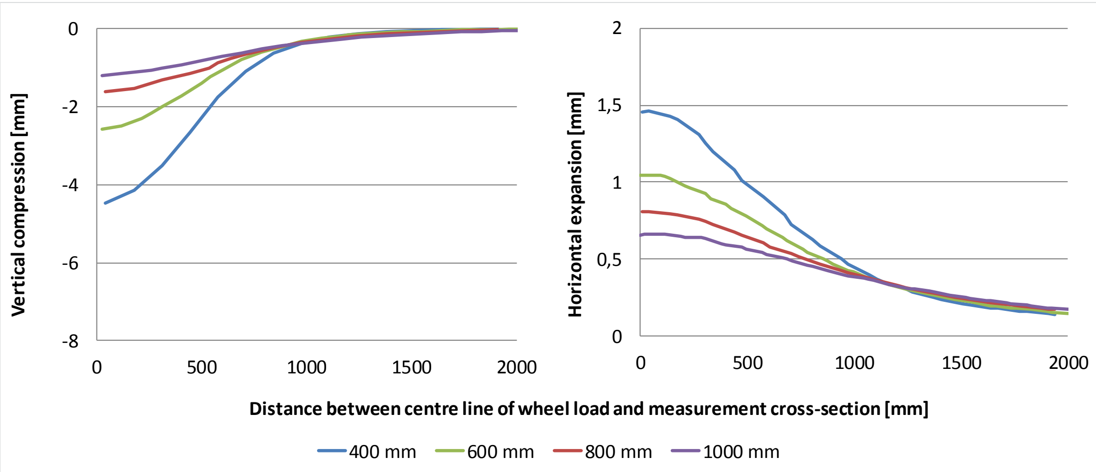

Figure 6: Effect of installation depth on FE simulated changes in the vertical and horizontal diameter of an 800 mm diameter plastic culvert.

In the second set of sensitivity analyses lower quality of structural layer materials and subgrade soil was simulated: in simulation 6 the structural layer materials were inferior, in simulation 7 the subgrade soil was inferior, and in simulation 8 both were of lower quality. The results presented in Figure 7 indicate that with a subgrade of reasonable stiffness, the quality of the structural layer materials is not very critical as regards distortions in an 800 mm diameter plastic culvert at an installation depth equal to its diameter. On the other hand, subgrade quality seems to have a marked effect on culvert distortions and, furthermore, in the case of poor subgrade soil, the quality of the structural layers is getting more important.

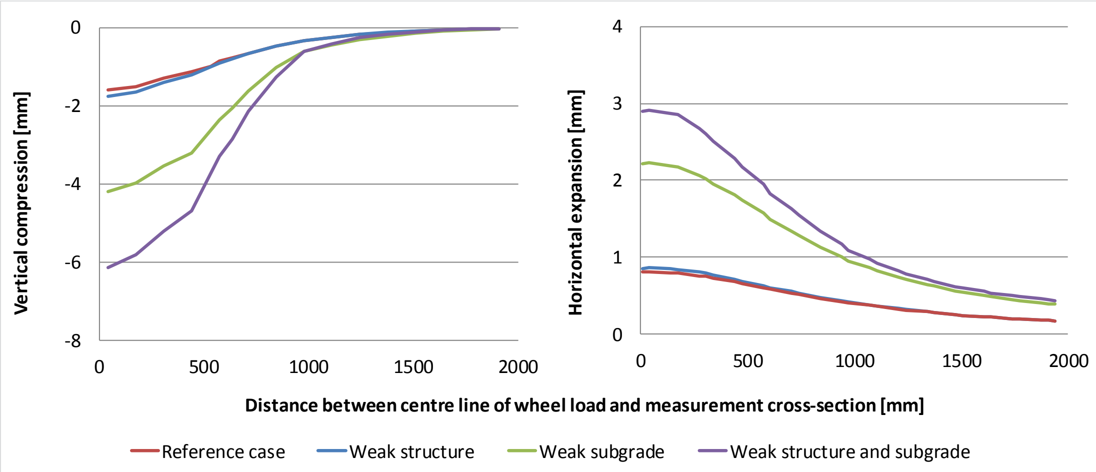

Figure 7: Effect of the quality of structural layer materials and subgrade soil on FE simulated changes in the vertical and horizontal diameter of an 800 mm diameter plastic culvert installed at a depth of 800 mm.

In the final phase of the FE simulations, the effect of the tyre configuration on the culvert distortions was analysed. Since it was considered self-evident based on earlier experience (Kolisoja;Kalliainen;& Haakana, 2015) that the effect would be marginal at an installation depth of 800 mm, only the effect at an installation depth of 400 mm was simulated. As Figure 8 clearly indicates, even at this shallow installation depth the effect of tyre configuration is very small. Thus it needs not be considered an important factor with respect to culvert distortions at any practically feasible installation depth.

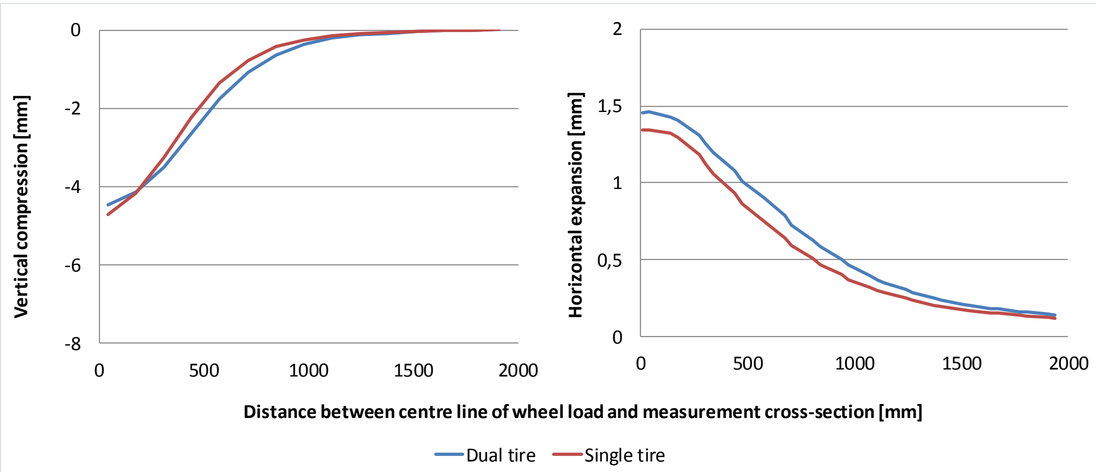

Figure 8: Effect of tyre configuration on FE simulated changes in the vertical and horizontal diameter of an 800 mm diameter plastic culvert installed at a depth of 400 mm.

5 Conclusions

Based on Finite Element simulations that were successfully verified by full-scale loading tests performed on a number of actual plastic culvert installation sites located on low volume gravel-surfaced roads, it can be concluded that installation depth is a critical factor as regards the distortions a corrugated HDPE plastic culvert undergoes subject to the loading effect of a heavy truck. Moreover, subgrade quality seems to have a marked effect on culvert distortions while the quality of the structural layer materials above the culvert is not all that critical, especially if the subgrade soil is not very soft. This observation stresses the importance of considering the overall performance of the culvert installation site, not only e.g. installation depth. Thus, not surprisingly, if a plastic culvert has to be installed at a fairly shallow depth in soft subgrade conditions, it is very important to backfill the culvert with properly compacted good quality aggregate material so as to provide the flexible culvert structure lateral support when it deforms vertically under an externally applied load. As regards the effect of the tyre configuration, it is not important in relation to culvert distortions at any practically feasible installation depth.

References

Arockiasamy, M., Chaallal, O., & Limpeteeprakarn, T. (2006). Full-Scale Field Tests on Flexible Pipes inder Live Load Application. *Journal of Performance of Constructed Facilities, 20*(1).

Brinkreve, R., Engin, E., & Swolfs, W. (2012). *PLAXIS 3D 2012. User Manuals*. The Netherlands: Plaxis bv.

CEN/TR 1295-3. (2007, 08 20). *Structural design of buried pipes under various conditions of loading: Common method*. Helsinki, Finland: Finnish Standards Association SFS.

Chaallal, O., Arockiasamy, M., & Godat, A. (2015). Filed Test Performance of buried Flexible Pipes under Live Truck Loads. *Journal of Performance of Constructed Facilities, 29*(5).

Kang, J., Han, T. H., Kang, Y., & Yoo, C. H. (2009). Short-term and long-term behaviors of buried corrugated high-density polyethylene (HDPE) pipes. *Composites: Part B, 40*, 404-412.

Kang, J., Jung, Y., & Ahn, Y. (2013). Cover requirements of thermoplastic pipes used under highways. *Composites: Part B, 55*, 184-192.

Kolisoja, P. (2014). Mode 2 Rutting Design Approach. *Report on Task D4 of the ROADEX IV Project, 58 p. Available at: http://www.roadex.org/wp-content/uploads/2014/01/ROADEX_report_Mode_2_rutting_design_approach.pdf.*

Kolisoja, P., Kalliainen, A., & Haakana, V. (2015). Effect of Tire Configuration on the Performance of a Low-Volume Road Exposed to Heavy Axle Loads - Response Measurements. *Journal of the Transportation Research Board, No. 2474*, 166 - 173.

Kraus, E., Oh, J., & Fernando, E. (2014). Impact of Repeat Overweight Truck Traffic on Buried Utility Facilities. *Journal of Constructed Facilities, 28*(4).

Molin, J. (1981). Flexible Pipe Buried in Clay. *Proceeding of the International Conference on Underground Plastic Pipe* (pp. 322-337). New York: American Society of Civil Engineers.

Moore, I. D., & Sezen, H. (2012). *Structural Design of Culvert Joints.* Transportation Research Board.

Sheldon, T., Sezen, H., & D., M. I. (2015). Joint Response of Existing Pipe Culverts under Surface Live Loads. *Journal of Performance of Constructed Facilities, 29*(1).

Spangler, M. (1941). *The Structural Design of Flexible Pipe Culverts.* Ames, Iowa: Iowa Engineering Experiment Station Bulletin No. 153.